Capital goods in the medieval economy, 800–1600: insights from illuminated manuscripts

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Abstract: This paper constructs an index proxying the use of capital goods and various technologies in the European medieval economy by analysing their shifting depiction in medieval manuscripts. Across the four main economic sectors of the European Middle Ages – farming, services, crafts, and construction – we find a significant rise in the use of a wide range of capital goods, reflecting increased economic activity. We document that most of this growth stemmed from the adoption and refinement of pre-medieval innovations. The results reveal greater economic dynamism in northern Europe, which by the end of the Middle Ages used considerably more capital goods than the south. We, attribute this in part to advances in transport efficiency in the north. Additionally, this study shows that the Black Death had little impact on capital intensity in medieval Europe.

Keywords: economic history, capital goods, Middle Ages, illuminated manuscripts

JEL codes: N13, N00, O16, E22

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1. Introduction

The Middle Ages were a pivotal period in the economic development of Europe. Not only did new institutions such as town councils, parliaments and the European Marriage Pattern arise, (Bosker et al 2013; Van Zanden et al 2012; De Moor and Van Zanden 2010), but production and transport were also revolutionised by medieval inventions such as the windmill and stern rudder (Langdon 2004; Mott 1996). Moreover, pre-medieval labor-saving inventions such as the watermill, the barrel, horse traction and the heavy plough are thought to have found much wider application over Europe (Reynolds 1983; Langdon 1986; Andersen et al. 2016).

Quantifying economic activity in this period presents significant challenges, however. Europe was politically fragmented. States did not develop nascent statistical apparatuses until the end of the Middle Ages. Moreover, many medieval accounts have been lost, and what did survive can be difficult to understand. This lack of data represents a serious challenge in testing theories of medieval economic development.

Historical national accounts that quantify the output of medieval and early modern economies do exist (collected in the Maddison project: Bolt and Van Zanden 2014). However, these series rarely cover the Middle Ages (the English series starting in 1270 by Broadberry et al. 2015 being an important exception). For other countries, the start of GDP series is significantly later, often post-medieval.

To obtain relevant information on this period – a long-term time series over consistent geographic units – requires alternative approaches as well. Various studies along these lines exist. An often-used proxy for economic development is medieval city size (Bairoch 1988; Bosker et al. 2013; Buringh 2021). Internationally comparable real wages are an important line as well (Allen 2001). Book production and human capital formation, the use of immovable capital goods, and church building have also been used in the past to characterize medieval development (Baten and Van Zanden 2008; Buringh and Van Zanden 2009; Van Bavel et al. 2018; Buringh et al. 2020).

On capital goods, however, quantitative information over this period is still lacking. The main exception is Broadberry and De Pleijt's (2021), who extend Feinstein's (1978) method to the 1270–1870 period for Britain. The exceptional source material in Britain that also allows for long-term supply-side historical national accounts (Broadberry et al. 2015), means they can reconstruct capital formation and stock using a perpetual inventory method

and adjusting for price changes. For most other countries, however, the source material is not available to create series running back to the medieval period with these methods.

This paper addresses this lacuna by using illuminations in medieval manuscripts to quantify the use of capital goods and technological change for the entire European continent, for the 800–1600 period. Our contribution with this paper is threefold. Firstly, we use the frequency of depictions of capital goods in contemporary manuscripts as a proxy for their actual medieval prevalence and thus for their use in the Middle Ages.[2] Our novel method of counting the numbers of some eighty different capital goods visible on dated illuminations in an extensive sample of surviving manuscripts permits us to estimate the contemporary frequency of their prevalence (an approach that also corrects for any losses of manuscripts over time). Our second contribution is that we classify the frequencies of depictions of capital goods into sixteen different fifty-year time periods, which allows us to discern actual medieval time trends in the period 800 to 1600. By covering manuscripts made in a large area of Europe we can also observe if there are geographical differences in the uses of capital goods between northern and southern Europe. The third contribution is that our index of the use of capital goods permits us to make inferences on the development of the capital intensity of the medieval economy.

We highlight that this approach cannot get level estimates of capital intensity or capital stock in the way of Feinstein (1978) or Broadberry and De Pleijt (2021), as we have no way of turning our measurements in a proper count of the number of capital goods, and we lack data on prices. However, our approach provides comparable measurements across time and space that can show overall changes in the use of capital goods and the shifting technological frontier in the medieval economy. In order to use this index we have to make sure that manuscript illuminations depict capital goods in a consistent way, a topic to which we turn in detail below. We will moreover argue that what we can observe about changes in price and quality of capital goods suggests that the results of our index should be seen as a minimal estimate of growth in the usage of capital goods in the medieval economy.

The lack of series on the use of capital goods hampers studies of the role of capital in the development of the preindustrial European economy. For example, Van Zanden (2009: pp. 244ff) runs simulations of the Dutch and

[2] In this paper we will from now on use the terms ‘frequency of depictions’, ‘prevalence’, and ‘usage of medieval capital goods’ interchangeably.

English economies on the basis of Cobb-Douglas models, but has to rely on assumptions about the returns on the capital stock to track the changing importance of capital. Broadberry et al. (2015: pp 388-389) argue that mixed farming in north-sea area made the region more capital intensive, because livestock was a form of capital, and required more capital goods. However, they lack comparative evidence stretching beyond England and before 1250. Pamuk (2007: 308–311) argues that changes in the capital/labour ratio were an important factor in the divergence between northwestern Europe and the rest of Europe in the later Middle Ages, but he has to rely on wage evidence to support this argument.

In this study we discern four main sectors in the medieval economy: farming, services, crafts and construction. Notably, we look whether we can distinguish an impact of the Black Death on capital intensity of the medieval economy (Pamuk 2007; Voigtländer and Voth 2013; Jedwab et al. 2022). We also investigate the role of capital intensity in the "Little Divergence", the starting point of the process where north-western Europe became more prosperous than the south (Allen 2001; De Pleijt and Van Zanden 2016).

This paper is structured as follows. The nature and some of the distinctive properties of medieval manuscripts and how we collected data on them are described in the second section (more details in Appendix A). The third section presents the steps we take to correct the data obtained from the manuscripts. Section four gives the results of the analysis for the main economic sectors and identifies which capital goods have contributed to these results. Section five discusses which phenomena may have biased our data and how we have minimized such biases. Conclusions finalize this paper.

2. Data collection of illuminated manuscripts

We use a novel data source to look at the use of movable capital goods in the Middle Ages. Manuscript illuminations, intricate drawings added to handwritten books, are used to measure the growing usage of capital goods and technological change in the Middle Ages. Manuscripts were created throughout the medieval period, at first mainly in monasteries for use by the clergy, but from the twelfth century onwards they were increasingly produced in lay workshops for an urban market, aimed at universities and lay readers (Buringh 2011).

These illuminations generally depicted religious, historical or fictional scenes, they often did so in a way that reflected daily life, including the use

of tools and other capital goods, and contain images of people doing their daily work. Though the total number motives in medieval religious books is limited, their pictures were as a rule never slavishly imitated. Even in a straightforward scene such as a crucifixion, the placing in the image of one or more crosses, the surrounding landscape and the size and spread of the spectators has countless variations. In this study we did not look at recurring art historical motives but rather concentrated on the technical details mainly visible in the staffage of an illumination. This staffage was often filled by the illuminator with details he knew from his own experience before becoming an artist. For instance, an artist might paint the birth of Christ – based on the text of the Gospels – as taking place in a landscape with a thick pack of snow including a windmill, both of which were unheard-of in oriental Bethlehem in the year 1 AD. Though there are numerous medieval copies of religious books which are textually completely similar, nearly all of them are different in their illuminations. A clear example is the famous ninth-century 'Utrecht Psalter'. Originally a French book, it has later been copied three times in England: the eleventh-century Harley Psalter, and the twelfth-century Eadwine and Paris Psalters. In the original Utrecht Psalter, which is presumed to have been based on a Classical example, the horsemen are riding their animals without stirrups. This was a recent technology introduced into Europe in the previous centuries and would certainly have been missing in the Classical exemplar possibly used for the Utrecht Psalter. However, while the copyists of the Harley and Eadwine Psalters tried to copy the drawings of the original as closely as they possibly could, they added stirrups, as by that time it was unimaginable how anyone could otherwise manage to ride a horse (see appendix A, figure A2).

While parts of illuminations reflected contemporary society, the question remains whether medieval illuminations can be trusted if they also picture one-legged foreign tribes, or cyclopes with just one eye, and flying machines propelled by griffins that transport people to the stars and back again? While these are fictitious pictures for us, for medieval people they were based on stories that they believed to be true, just like stories from the Bible, of which there were no eyewitnesses either. These stories were lavishly illustrated in the Middle Ages, often with local and contemporary details in the staffage to make them credible for a viewer.

In this study only those images of actual devices have been included in the analyses that have been corroborated by material finds from medieval archaeology. Therefore medieval images of flying machines and submarines have been discarded from the analyses (Appendix A shows which items have been included in the data assembly). Other researchers before us have used

medieval images as a valuable source for contemporary life. When utilizing manuscripts as evidence for medieval agricultural practices, Moorhouse and Bond (2016, 17) conclude that the varying detail amongst the same scenes suggest that the images reflected reality, and that they can be used to represent contemporary life in the area where the manuscript was illustrated. Similarly, Anthony Bryer (1986, 52) concludes that Byzantine illuminations offer fresh and realistic clues about medieval tools, especially wooden ones otherwise lost to documents and archeology. Richard W. Unger (1991, 61) studied the medieval depictions of Noah as a shipbuilder. He concluded that with a few exceptions, the pictures of Noah and his ships closely follow the development in the design and construction of contemporary European ships. More recently, Lillian Ray Martin (2001, 141 ff) collected medieval pictures of Venetian ships and boats and integrated those with historical and archaeological evidence. For the European construction industry, architectural historian Günther Binding (1993) has made valuable contributions about medieval building practices based on visual information in contemporary manuscripts next to the textual and archaeological sources that he consulted. Perrine Mane (1987) has used images in illuminated manuscripts to describe the work of medieval coopers. In his book on the history of the watermill Terry S. Reynolds (1983, 97) has dedicated a whole chapter to the iconography of the medieval vertical waterwheel. These very different contributions covering widely varying fields, show images in medieval manuscripts are used to represent the society they were created in. They therefore can be a reliable source of information, when used wisely.

The data is found on illuminated pages in mainly Christian manuscripts and is concentrated on Europe in the period 800 to 1600. Few books survive prior to 800, and those that do, convey little information on capital goods. Shortly after 1450 the printing press was developed. Over the next century the character of manuscripts changed, as they were outcompeted by cheaper printed books. In the sixteenth century expensive handwritten books had become a niche market and their numbers decrease sharply (Table 1). By counting the prevalence of some eighty different capital goods a picture can arise of the variations in their use over time. These implements have been scored in a database. Their pictures were found in over 74,000 illuminated pages in nearly 11,000 manuscripts.

Table 1. Number of manuscripts, illuminations, and manuscripts and illuminations with capital goods, by century and region. Source: database

	manuscripts		with capital goods		illuminations		with capital goods	
century	north	south	north	south	north	south	north	south
9th	397	129	58	17	2574	1146	305	120
10th	242	192	36	45	1288	1399	119	207
11th	533	356	107	81	3353	2136	506	347
12th	687	345	202	55	3393	1845	679	284
13th	957	270	392	88	5831	2483	1780	998
14th	943	593	517	254	9150	3850	3648	1147
15th	2584	1554	1672	500	19691	6062	8035	1833
16th	596	285	375	122	7346	1137	2345	410

The pictures that filled the database were found in a collection of over three thousand books that have previously been used to estimate manuscript production in the Latin West (Buringh, 2011). Each different illuminated page of a manuscript with a picture in the library forms a separate entry. For every entry a number of essential descriptors are included. The purpose of this database is to allow a peek at the contemporary uses of medieval technologies. A potential source of bias is that we rely on published or digital versions of medieval manuscripts (facsimiles) for the images of medieval illuminations, and the publication process itself may have been selective. Art historians deem some manuscripts more important than others, which could result in a publication bias. Certainly, the library that was used contains pictures of only a (unknown) fraction of all surviving illuminated manuscripts, and could be considered to be biased to some extent. However, both previous objections are not relevant in any way for this study. In deciding whether or not to include a manuscript into the current database, the occurrence of an image of some medieval implement never was a criterion. Every individual manuscript reproduced in the library with one or more illuminated pages was included in the database, including many manuscripts that do not picture any of the eighty capital goods analyzed in this study. This novel approach allows us to establish per fifty-year time window the frequency with which a certain medieval implement has been pictured in a sample of all illuminated manuscripts that survive from that period. As we track the share of manuscripts, our approach automatically corrects for changing loss rates of manuscripts over time. This approach also corrects for the bias of scenes that were pictured repeatedly in one and the same

manuscript. Our approach would only lead to biased results when manuscripts containing images of medieval capital goods would influence the actual survival of the manuscript in question. There is no evidence at all for such an assumption to be true (see Buringh, 2011, 179ff).

Some items are excluded from our analyses because they are too rare. While nearly 11,000 handwritten books with illuminated pages are included to maximise precision in our estimates; nevertheless, some medieval items were pictured so infrequently that they remained under our cut-off criterion of 32 items and fell out of the analysis (such as the adze, alembic, armillary sphere, astrolabe, etc., see the alphabetical list in Appendix A.1. compared to Table 2). Even when an item narrowly surpasses this cut-off criterion, standard deviations often remain high.

We distinguish the following main economic sectors in the Middle Ages: farming (agriculture and husbandry), services (such as milling, medical care, transport and long-distance trade), crafts (artisans and trades, local commerce and fishing) and finally construction and building activities. For each of these sectors around twenty capital goods that can be regularly (at least 32 times over the entire period) found on illuminated pages were selected and scored for the database and analyzed in this study.

Generally, we prefer to analyse trends in the overall depiction of capital goods or in these sectors rather than individual capital goods as trends in the latter can easily be affected by small sample sizes. However, in appendix A.2. we validate the data collected here by tracing a number of specific depictions where we have strong priors about the trend over the medieval period.

Table 2. Medieval capital goods or activities regularly found on illuminated pages. *Capital goods with an * are medieval inventions. All the other capital goods were already known by the year 800.*

Farming	Services	Crafts	Construction
Ard	Anchor	Anvil	Capstan
Axe	Barrel	Barrel	Chisel
Beehive	Bier	Bellows	Compass
Flail	Boat	Capstan	Crane
Harrow	Cart	Cleaver	Demolition
Hayfork	Cauterization	*Clock	Drill
Heavy plough	Healing	Cogwheel	*Flying scaffold
Hoe	Horse collar	Crank	Hammer
Horse collar	Millstone	Distaff	Hook
Pickaxe	Pack animal	Drill	Ladder
Press	Pulley	Fishing rod	Mason
Pruning knife	Ramp	Furnace	Measuring
Rake	Sledge	Gridiron	Mortar
Screw	*Stern rudder	Hammer	Nails
Scythe	Transport	Key	Pincers
Sickle	Urine flask	Loom	Plumbline
Spade	Wagon	Nails	Saw
Trident	Watermill	Net	Scaffold
Winnowing basket	*Wheelbarrow	Oven	Treadwheel
	Yoke	Pestle	Trowel
		Pincers	*Wheelbarrow
		Saw	
		Screw	
		Spindle	
		Spit	

Generally, medieval manuscripts contain no date of their production and were only dated centuries after their creation, with considerable uncertainty. Similarly, they often do not carry a place of origin either. The first issue results in date heaping, meaning an overrepresentation of manuscripts that got assigned dates with round numbers. Section 3.1 describes how this is overcome. Because of the low numbers of manuscripts picturing items in certain time windows, a distinction has been made between just two geographical and cultural regions: ‘north’ versus ‘south’. The ‘north’ covers France together with all the other European countries located on a more northerly latitude than France. The ‘south’ encompasses the Iberian

Peninsula, Italy, the Byzantine Empire, and countries with a predominantly Eastern Orthodox faith.[3]

A further issue is that some of the activities that have been scored, are heavily concentrated in a few manuscripts. For instance, most activities of a doctor or quack, have often been pictured in just a few medical manuscripts. Their distribution over all illuminated pages is skewed, meaning that the chance of finding this item within a random sample of illuminated pages is not uniformly distributed. Therefore, the unit of the analysis in this paper is the manuscript itself. If a given capital good is pictured at least once in a manuscript, it is counted as a one and otherwise it is zero. What is reported in this paper is the chance of finding a manuscript within a certain time window depicting one or more specimens of the capital good or activity as a fraction of all illuminated manuscripts in that time window.

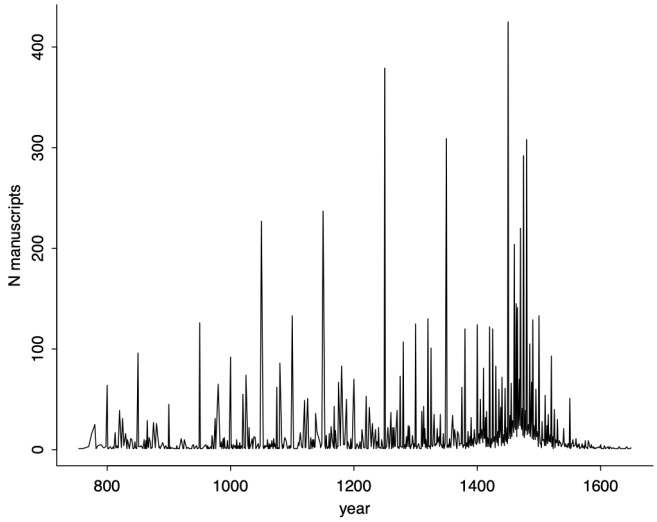
A different complication of medieval manuscripts is that the degree of realism in their illuminations has gradually increased over the 800-year period. This means that the chances of finding a certain capital good in a picture will have changed as well. One can imagine that in more realistic and often increasingly detailed later paintings more capital goods will have been represented than on the rather primitive or symbolic images at the beginning. This means that all the data have to be detrended to overcome this problem that would lead to a systematic bias – if left untreated. Section 3.3 describes how we addressed these issues.

[3] The North/South distinction can be used to

3. Data treatment of illuminated images

3.1. Date heaping

Figure 1. Distribution of manuscripts over assigned production dates.
Source: see database



The high peaks in Figure 1 show that manuscripts with round dates such as 1450 are overrepresented in the sample. This has to do with the lack of precise dating in manuscripts. They have often been assigned a round date, such as the fifteenth century, with 1450 as its central date. In the fifty-year time windows, all manuscripts with such round dates have been treated using a weighted interpolation. For each capital good, all q_t^h (heaped) manuscripts with a round year (ending in 50 or 100) have been distributed proportionally over the preceding *t – 1* and next *t + 1* time window to arrive at a heaping-corrected number of manuscripts q^*. Distributing the manuscripts from round years over the preceding and previous time period was done as follows:

$$q_{t-1}^* = q_{t-1} + q_t^h \frac{q_{t-1}}{q_{t-1} + q_{t+1}}$$

$$q_{t+1}^* = q_{t+1} + q_t^h \frac{q_{t+1}}{q_{t-1} + q_{t+1}}$$

3.2. Estimating chances of finding a capital good.

Let q_t be the total number of manuscripts in time window t and let q_{ct} be the number of manuscripts containing one or more images of capital good *c* then the chance, p_{ct}, of finding a manuscript depicting such a capital good in time window t is calculated by:

$$p_{ct} = \frac{q_{ct}}{q_t}$$

3.3. Detrending the long-term increase in realism in illustrations.

Over the study period the degree of realism has increased, from rather crude representations in the beginning, to illuminations that strived for realism by the end. As increasing realism will have led to more capital goods being pictured, the in 3.2. calculated p_{ct} will have to be detrended. This has been done by creating a series on the basis of three different everyday objects that are neither themselves capital goods nor would we expect them to have become more prevalent in medieval society. This allows us to establish a synthetic baseline or 'counterfactual' for realism in medieval manuscript illuminations that would have occurred even if there were no increase in capital intensity. We then use this series to adjust for broader trends in artistic realism in the depiction of capital goods. The everyday objects we used for detrending and that have been depicted frequently in manuscripts are trees, chairs, and musical instruments. Again, every illuminated page on which one or more (parts of) trees, chairs or musical instruments were visible has been scored (see Appendix A for the overall database construction and appendix C for our "realism" series).

Before they are used for detrending the chances of finding a tree, a musical instrument, or a chair in time window *t* have been normalized because the frequency with which they each are pictured differs. Next, these three series are combined to remove noise in the individual series. This combined realism index was created as follows for time window *t* and for *K* subperiods:

$$p_{rt} = \sum_{i \in R} \frac{1}{K} \frac{p_{it}}{\sum_{j=1}^{K} p_{ij}}$$

In appendix C we revisit our results using only a single correction measure (either only trees, musical instruments or chairs), the calculation of which

follows from the formula given above. All results presented in the main text paper have been detrended using this combined correction measure, indexed at 1450. The values thus obtained are shares of manuscripts depicting a given capital good at levels of realism as in 1450. This detrended chance p_{ct}^{d} of finding a capital good *c* in time window *t* is:

$$p_{ct}^{d} = \frac{p_{ct}}{p_{rt}}$$

For the two subsamples 'north' and 'south' the correction yardsticks have been calculated separately and applied to each of the subsamples. Appendix C provides the series used to correct for realism and our main results recalculated for each of the separate subindices.

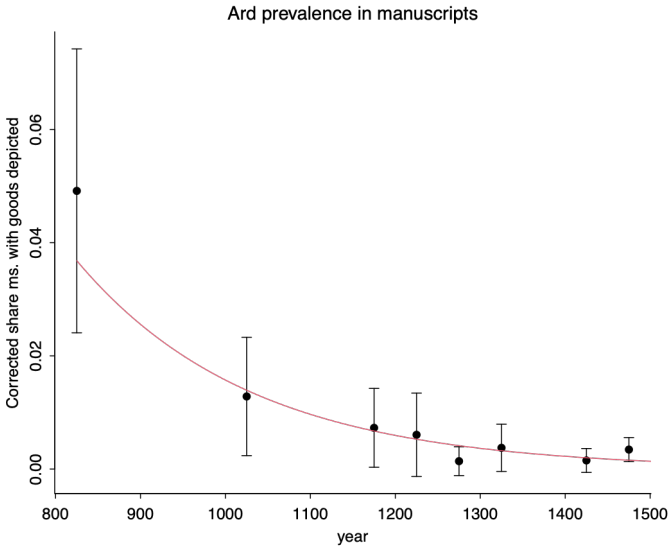
3.4 Capital intensity

By quantifying the frequency of capital goods in manuscript illustration, we approximate the capital intensity of the medieval economy, not the capital stock. This is because the number of manuscripts in our database effectively serves as a population correction. In fact, the total numbers of all manuscripts produced per century in the Latin West between 800 and 1500 increased more than twentyfold, while the total population only increased three to fourfold (Buringh 2011, 162). Unfortunately, while we have access to estimates of manuscript production per capita, we do not have the necessary illuminated manuscripts per capita series that we would need to calculate capital goods on a per capita basis. Illuminated manuscripts are a fraction of all produced manuscripts. Our series should be considered a lower bound for the actual per capita trends.

3.5. Missing data

Some capital goods were rarely pictured. The count for such capital goods can be zero in a time window by chance alone, even though we know such capital goods to have been in use. When a capital good is found most of the time and by chance not pictured in a specific time window it would be wrong to conclude to a zero prevalence in that specific fifty-year period, so we code these as missing. An example of such a sparingly depicted capital good with missing values, is the ard, the prevalence of which is shown in Figure 2.

Figure 2. Detrended prevalence of the ard or scratch plough (with 95% confidence intervals). Source: see database.



The ard was used all over Europe in the first millennium to prepare the soil for tilling cereals by ploughing. Some of the earlier fifty-year time windows do not contain any pictures of ards. It would be wrong to assume that no ards were used at all in Europe in this period, as the population in the tenth century could not have been sustained without them. They were not found because of the sampling and survival process.[4] Figure 2 shows that – with missing values – their prevalence has decreased exponentially over time ($p < 0.01$), while if we set these missing values to zero no trend is statistically distinguishable.

In what follows, we treat all cases of zero prevalence as missing values. However, for all *new* medieval inventions (an * in Table 2) the values of zero before their first prevalence in the database is treated as actually having a value of 0 in the analyses below. These new capital goods were not yet invented and their prevalence was indeed 0. To be more precise, in the period of around a century before their first image they probably had a prevalence

[4] In the 50-year time window of 925 there were in total 110 manuscripts in the database and in 975 the total number of manuscripts in the database was 324. The chance of not finding an ard (with its average chance of 0.0027 during the whole study period) is 0.9973. For 110 manuscripts in the period around 925 it means that with such a chance (0.9973^110) there is 74% chance of finding no ards at all in any of these 110 manuscripts. For the 324 manuscripts in the period around 975 this chance still is 42% (0.9973^324) which indicates that there is a serious chance of missing ards in the database because of the low frequency with which they are then found and the relatively small numbers of manuscripts involved.

still very close to zero as it generally takes one century before a new invention shows up in illuminated manuscripts (see Section 5.1 and Figure 8). Unger (1980, 22) indicates that it is commonplace in medieval technology that developments occurred at least fifty years before the date of the earliest known evidence, and for changes in ship design this time span is even greater (see also White 1962: 25).

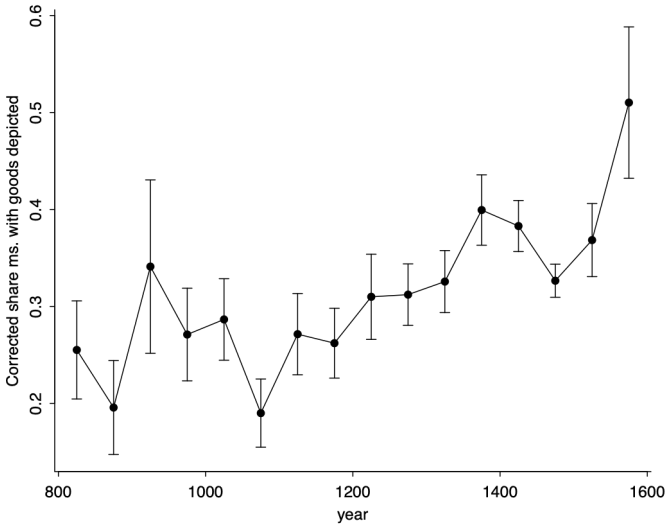
3.5. Testing for statistical significance

As an indication of significance, the linear regression coefficient and its standard error have been calculated of the detrended chances of finding a specific capital good in the sixteen time windows between 800 and 1600. In our discussion below we report trends as statistically significant if the p-value is lower than 0.01. Because some eighty different capital goods were tested, a stricter threshold criterion seems to be justified to later prevent chasing noise when interpreting the results. In addition, we also estimate regression models that allow for measurement errors in our estimates of the prevalence of capital goods (McElreath 2016). Because these errors are generally larger in the earlier and later period, both with fewer manuscripts, they could introduce bias in our trend estimates. Finally, we also estimate the trends using Poisson regressions of the count of manuscripts on a time trend. Appendix B reports the results of these two alternative approaches. They yield similar results as our main approach reported below.

4. Results

4.1. Overall and sectorial results

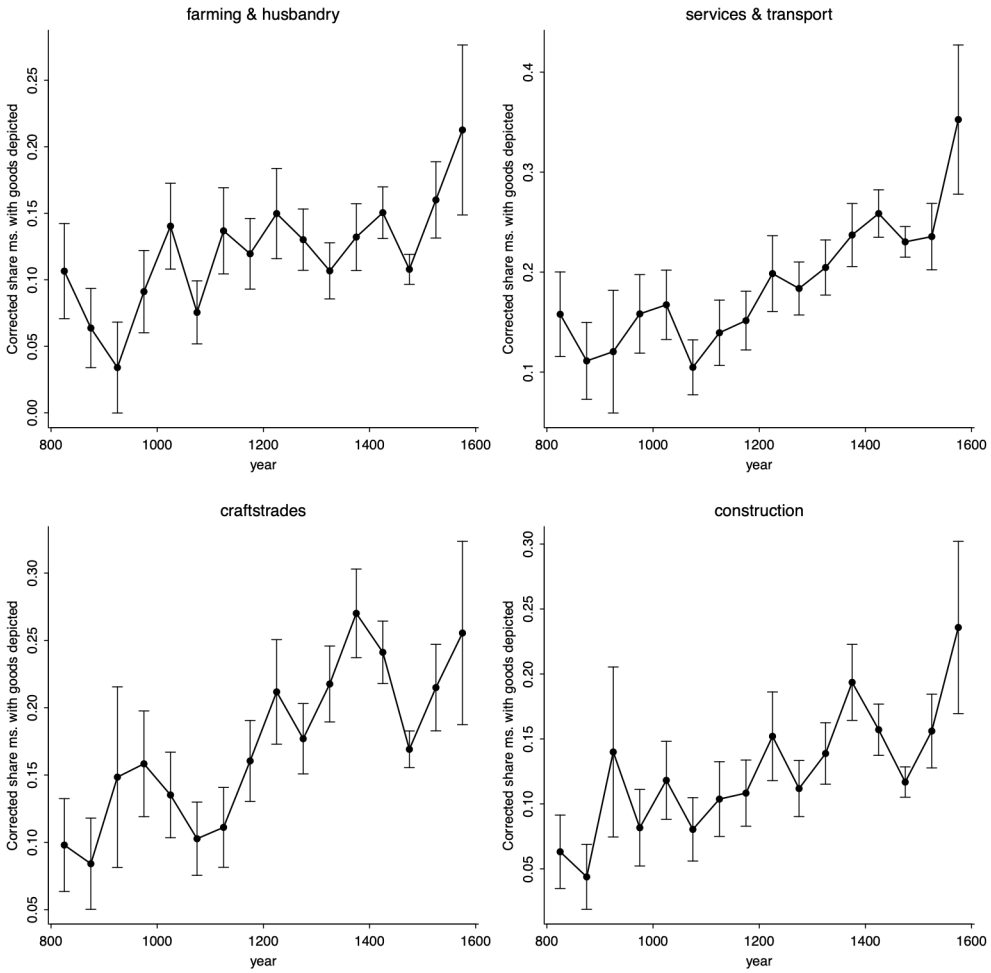
Figure 3. Capital goods in the medieval economy (all sectors), 800–1600 in arbitrary units, with 95% confidence intervals. Source: database.



Figures 3 and 4 show the trend in the use of capital goods in the medieval economy, and its four main sectors respectively. All four medieval economic sectors show a statistically significant ($p < 0.01$) increase in associated capital goods in the full sample. Overall, depictions of capital goods increased 7 percentage points per century, suggesting a 50 percentage point increase over the entire 800–1600 period. Strong, sustained growth can be observed between 1100–1400.

Additionally, we observe downturns following the Carolingian period and after 1400. The implications of this final decline for the notion of high capital intensity post-Black Death are explored below. We also emphasise the uncertainty of some of our estimates. The 95%-confidence intervals can differ substantially in size. Especially in the early and later period confidence intervals are wide because of the low numbers of items and manuscripts in various time windows. While growth over the entire period can be confirmed, the difference between two consecutive time windows generally lack sufficient precision for conclusions on changes in their prevalence.

Figure 4. Capital goods in four sectors of the medieval economy (with 95% confidence intervals). Source: database



Before examining trends in capital intensity across different sectors of the medieval economy, it is useful to discuss the size of the farming sector in circa 1600. It made up around 30/40/55 % of GDP and 40/60/65 % of the labour force in Britain, the Netherlands, and Italy respectively (Broadberry et al. 2015; Van Zanden 2002; Malanima 2011). These were all relatively advanced economies with large manufacturing and service sectors, so we should expect the size of the agricultural sector to be higher in Europe as a whole (maybe 60% of GDP; 70% of labour force), and higher still around 800. Services would have been the largest part of the remainder, followed by crafts and construction.

All four sectors experienced substantial increases in the depiction of capital goods, with each showing a rise of approximately 7 percentage points per century. Turning to individual trends of different capital goods, in the service

sector 35% of the capital goods increased significantly. For farming this was 26% and for construction 29%, while for crafts 28% of the capital goods increased significantly in their prevalence.

Most individual capital goods in the service and transport sector saw a statistically significant increase of 0.2 to 4 percentage points per century. The exceptions were millstones and carts. The decline in cart usage is attributed to the replacement of two-wheeled carts with four-wheeled wagons. Drawn by horses instead of slower oxen, four-wheeled wagons transported double the load of carts while requiring only one driver. Wagons also exerted less pressure on the ground, improving performance on uneven terrain despite being more expensive (Langdon 1986).

New inventions in this sector include the wheelbarrow (twelfth century), doubling the loads that could be transported by a single man; and the stern rudder (eleventh century), making for a substantial improvement in the sailing qualities of vessels in rough seas. Urine flasks also increased significantly in their prevalence. They were the medieval symbol of doctors, and the colour of urine was one of the main means for doctors to come to a diagnosis.

In the farming and husbandry sector five of the nineteen goods increased significantly. We can see the heavy plough supplanting the ard, just like Andersen et al (2016) have shown. While the heavy plough was known, the use of the ard was near-universal at the start of the medieval period. The heavy plough turns the sod rather than just scratching it. While more expensive due to the use of more metal and the larger traction train that it needed, ploughing once sufficed with a heavy plough. This allowed more cereals to be grown, which in turn lead to a higher demand for milling. Another capital good that was increasingly depicted in manuscripts was the spade, especially in the North (as was the rake). By the end of the period, spades were also increasingly made of metal rather than wood, representing a larger investment and enabling a higher productivity. Other farm implements increasing in prevalence were the press, rake and trident.

In the construction sector the prevalence of six capital goods increased significantly in the full sample: the hammer, ladder, drill, nails, treadwheel and the wheelbarrow. The pre-medieval treadwheel was a more than man-sized wooden wheel in which people walked upright to let it rotate. Using a rope and pulleys the rotating axle in combination with the force by the weight of the walkers was used to lift heavy loads with a crane. Nails were then always handmade by smithies and because of the increasing use of iron their price gradually decreased making them more common.

Mechanical clocks driven by weights were a thirteenth-century invention, that spread over Europe fast. Clock making is a marker for the fine mechanical skills developed by the time. Cogwheels were also used in mills to change the direction of motion induced by the vertical waterwheel (or sails) into a horizontal motion driving the millstones, and as a gearing mechanism to adjust the speed with which these devices were turning. Cogwheels in various sizes are a complex form of mechanical engineering that expanded considerably during the Middle Ages. The medieval wooden barrel was used similarly as our modern container. Barrels were strong and protected their contents from rough handling and from the elements during transport. Because of its bilge a barrel could be easily rolled or turned by one man, who could so manage a considerably larger weight than he could possibly ever have carried.

4.2. Increasing capital intensity

The trends presented above are based on the increase in the numbers of capital goods. Gradually, however, the character of various capital goods changed too. For some capital goods this qualitative transformation could have been as important as their quantitative increase. For example, over the study period the prevalence of vessels rose approximately by a factor of three. However, ships became considerably larger in that period, from one-masted ships with either a square or a lateen sail to full rigged three-masters that could carry more freight, and were equipped with a stern rudder that could sail faster and in rough seas, thereby increasing the length of the transport season. All these different qualitative developments drove medieval transport costs down considerably. The costs of such bigger and better boats were higher, leading to an increasing capital intensity. Through their higher labor productivity these improved capital goods more than made up for the increased costs.

The watermill is a capital good that increased in prevalence, though not significantly. From simple, small horizontal watermills in the beginning, they developed into the more complex and expensive, larger vertical watermills used later in the Middle Ages. Watermills at first had undershot waterwheels, but over time the even more powerful overshot wheels eventually drove about half of them. An overshot wheel needed more expensive waterworks to supply the higher water level that was necessary to power it. Therefore the medieval watermill shows a gradually increasing capital intensity. Millstones came in different qualities and prices depending on the type of stone that was used to make them. A large part of the cost of the heavy millstone were its

transport costs, especially when this journey was partially overland. The larger and more powerful vertical overshot watermills used larger and more expensive millstones, so here too capital intensity increased.

The discussion of the individual capital goods above shows that this qualitative improvement of medieval devices was not an exception. What complicates the visibility of such changes is that it could take a century before a new item or application was pictured. The quantitative approach followed here by counting the prevalence on contemporary illuminations only shows growth on the extensive margin, like Broadberry and De Pleijt (2021). A full picture also requires including the various qualitative changes and improvements in the pictured implements. What is clear is, however, that such gradual changes in the quality of most of the medieval devices are hard to spot in contemporary images. Gradual changes in technology have nevertheless led to a higher capital intensity over time.

4.3. More dynamism in the ‘north’

The database allows to explore whether capital intensity trends differed between northern Europe, here called ‘north’ and the ‘south’. In the north, the farming, services and crafts sector displayed growing use of capital goods, whereas in the south their use stagnated, suggesting a more dynamic northern Europe.

A greater dynamism in the north can be substantiated if we consider in which regions some of the crucial medieval inventions are believed to have taken place. The stern rudder was probably developed in the Nordic seas around the eleventh century. The windmill was likely developed in the southern North Sea area somewhere in the twelfth century. The same goes for the wheelbarrow, which widely increased labor productivity in transport and construction. Another example is the barrel. Barrels were for medieval commerce what containers are today, and by their ease of handling and transport were essential for commerce. They were used significantly more over time in the north, whereas in the south, the barrel prevalence did not increase.

Figure 5. Capital goods in the four economic sectors in 'north' and 'south', with 95% confidence intervals. Source: database

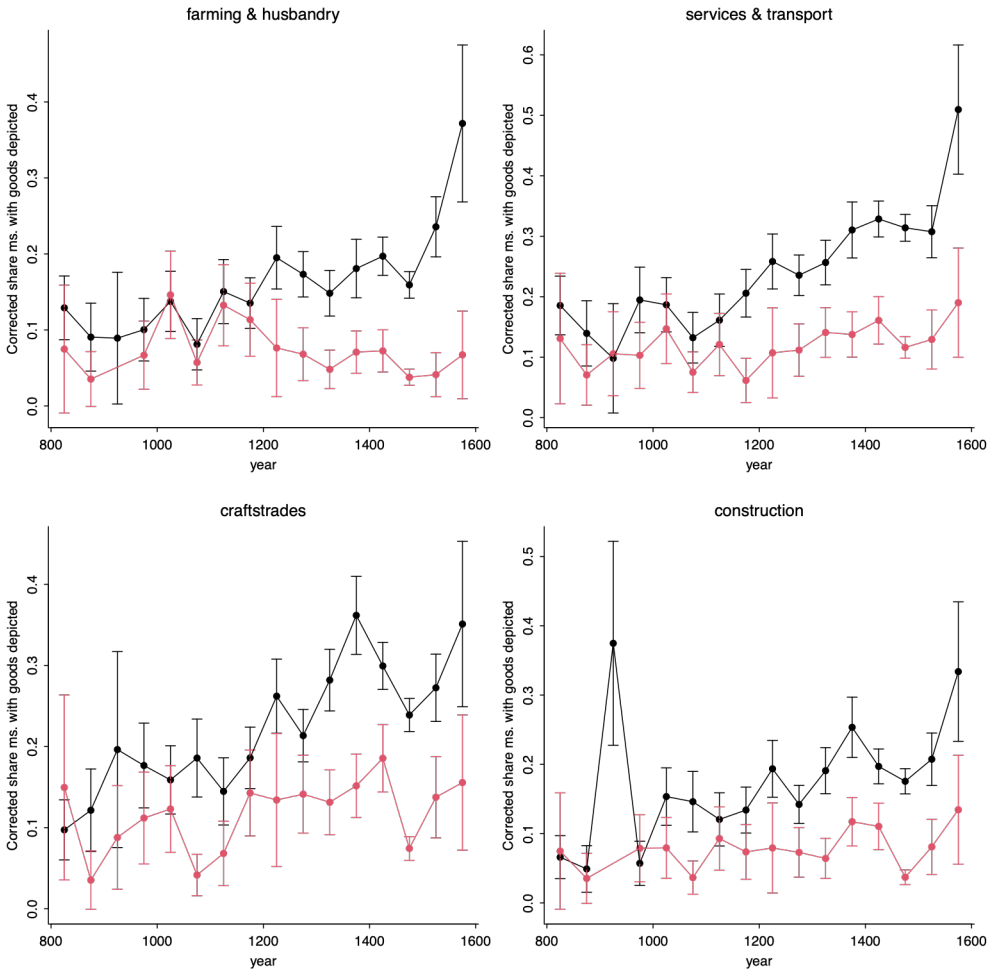


Figure 5 shows striking differences in the use of capital goods in the north and south. Before the thirteenth century, depictions of capital goods in both regions were at similar levels. After circa 1200, however, farming—the largest economic sector in both areas—used capital goods at a markedly different rate. Across all sectors, capital goods increased significantly in the north while remaining at similar levels in the south.

The fact that the use of capital goods increased more in the north than the south across all economic sectors suggests that potential explanations should transcend a single economic sector. While high urbanization rates are often associated with highly productive agricultural sectors, the north-south divergence in capital goods use, despite potentially differing urbanization

trajectories, points to other fundamental differences.[5] We suggest that varying relative transport efficiencies – both over land and over sea – constitute a substantial difference between the north and south that can bridge these observations.

In the north, horses gradually superseded the slower oxen for hauling freight over land after the tenth century (Langdon, 1986), a shift that did not occur to a similar degree in the south. This led to more than double the transport efficiency of freight over land in the north by the second half of the thirteenth century, gathering further momentum afterward (Buringh, 2025). This meant, for example, that farmers in the north could reach a five to six times larger market compared to their counterparts in the south, with a similar human effort.

For transport over sea, similar distinctive developments took place between north and south. In the north, the stern rudder was introduced after the eleventh century, enabling ships to deal with rougher seas and extending the regional sailing season. This and other shipping improvements led to higher efficiency in transporting cargo over sea in the north. In the Mediterranean, regular wars and the permanent threat of pirates forced freight ships to carry heavy guns, sail with larger crews, leaving less room for cargo, making them less economical. These regional threats not only concerned southern ships but also those visiting from the north, which were less than half as efficient when sailing in the Mediterranean compared to what was regular on ships sailing locally in the north. These developments led to a substantially lower transport efficiency over sea in the south.

Together, these differences in transport efficiencies over land and sea explain the dissimilarities in the use of capital goods between north and south markedly better than regularly presented explanatory factors such as regional urbanization rates and absolute urban populations (Buringh, 2025). Improved

[5] Different patterns of urbanisation also drove the extent of regional feudalism. The lack of urbanization in the north made that after the first millennium feudalism could develop fully there. Feudal lords in the north had an interest in actively investing in their hereditary fiefs to increase their income and consolidate a future income for their descendants. For instance, feudal lords invested in watermills (and later windmills) to generate extra income, and with such investments were promoting mechanization in the north. The larger southern (and often self-governing) cities prevented the full development of feudalism. This often led to a domination by the city of the surrounding countryside (*contado*) right up to the very borders of the ecclesiastical diocese (Epstein 2006). Southern cities had an extractive hold on the *contado*, and there was less incentive to invest in farming. For the Byzantine Empire, Lailou and Morrisson (2007, 239) state that a major difference was that the Byzantines did not develop a seigneurie banale, which was so important for the feudal revenues in the Latin West. Extraction from the countryside and the ensuing lower levels of investment have contributed to a lagging farming sector in the south, as is suggested by Figure 5.

transport meant, for instance, that crafts and farming in the north gained access to considerably larger markets, allowing for greater specialization (a Smithian explanation). Furthermore, the important grain markets could function better with lower transport costs. This enhanced market integration and specialization fostered a more dynamic northern economy, reflected in the increased use of capital goods.

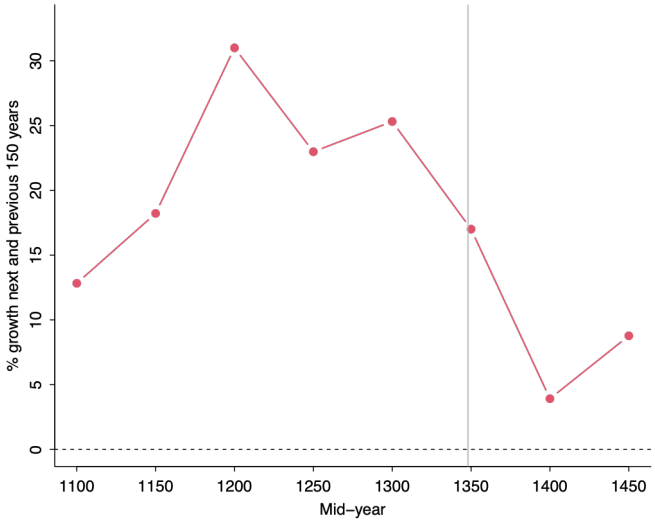
While these substantial differences in transport efficiencies seem to explain the lower dynamism, as shown by a lower prevalence of capital goods in the south at the end of the medieval period, other explanations might also play a role. For instance, the European Marriage Pattern (EMP), which first developed in the north after the Black Death in the later Middle Ages, is suggested to have led to faster economic development in the north (De Moor and Van Zanden, 2010). However, as Figure 5 illustrates, a higher use of capital goods in the north largely predates the Black Death, which makes it dubious to see the EMP as the sole explanatory variable. Instead, the persistent divergence in capital good usage suggests that fundamental differences in economic organization and market integration, driven by transport efficiencies, were already shaping the economic landscape before and after the Black Death, paving the way for institutional developments like the EMP to further consolidate northern economic advantages.

4.4. Capital intensity after the Black Death

The Black Death is often considered a pivotal moment in the development of the European economy. It led to higher wages as labour became scarce and is connected to the rise of the European Marriage Pattern. Another key point is that on paper the European economy suddenly became more capital intensive, as a considerable fraction of the people had died but material objects persisted.

Our data allows us to assess this claim in more detail. We first consider the smoothed growth in depictions of capital goods before and after the Black Death. Figure 6 shows the average growth in percent of capital goods between two consecutive 150-year periods. It shows that growth after the Black Death (in 1350) decreased relative to the boom years 1200–1350, though always it remained positive.

Figure 6. Growth in percent of capital intensity averaged over 150-year periods. Source: database.



We can also analyse the trend in the two hundred years before and after the Black Death (1348-1352, here the periods 1150-1350 and 1350-1550). Table 3, models 1 and 2 below compare the levels before and after the Black Death, showing that the capital intensity as measured by the prevalence of their depictions in medieval manuscripts was slightly higher after the Black Death than before (0.4 percentage point). However, this could be part of a long-term upward trend that we have documented above. To see whether the post-BD also deviates from the trend, we estimate the trend before and after 1350. Model 3 show that the post-BD trend is negative and small. If we look at the half-century estimates in detail (model 4; Figure 6), we can see that the first hundred years after the Black Death shows 0.3 percentage point higher capital intensity, but that this drops again after.

Table 3. Modelling the trend before and after the Black Death. Outcome variable scaled to 0–100 for legibility of estimates. Standard errors (between parentheses) clustered by capital good. Significance codes: ***=0.001, **=0.01, *=0.05.

Dependent Var.:	Percent of manuscript w. capital goods (detrended)			
Constant	1.76***			
	(0.220)			
post-BD	0.392***	0.423***	3.76	
	(0.102)	(0.103)	(2.56)	
period			0.002*	
			(0.001)	
period x post-BD			-0.003	
			(0.002)	
period = 1175				-0.576**
				(0.185)
period = 1225				0.036
				(0.146)
period = 1275				-0.586***
				(0.116)
period = 1375				0.316*
				(0.132)
period = 1425				0.214*
				(0.095)
period = 1475				-0.354**
				(0.106)
period = 1525				0.441*
				(0.173)
Fixed-Effects:				
capital good	No	Yes	Yes	Yes
S.E.: Clustered	by: capital good	by: capital good	by: capital good	by: capital good
Observations	570	570	570	570
R2	0.00793	0.83765	0.83930	0.85647
Within R2	--	0.05339	0.06297	0.16310

Though this result might seem unexpected, it can be explained by the short economic life of the mobile medieval capital goods observed in this study. Generally, movable capital goods like ships, wagons or farm implements should be expected to last at most some thirty years. Therefore, at any given

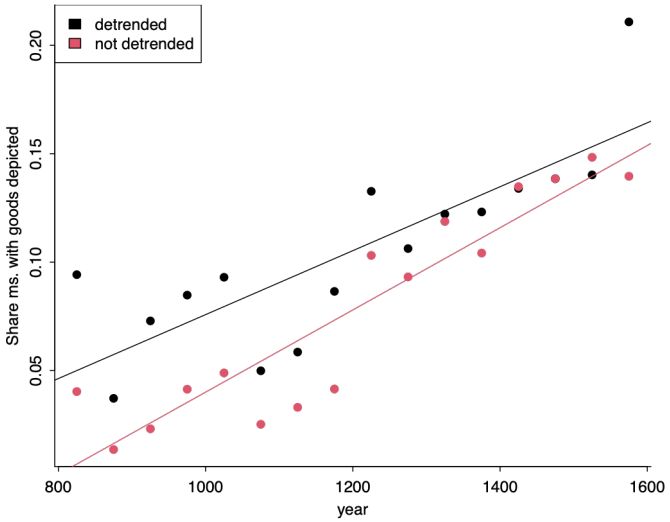
year, the European stock of such capital goods can be expected to still have had a life expectancy of fifteen years or less, which is not substantial when viewed over the 50-year time windows in this study. Because of the increased relative demand for labour after the Black Death, it seems safe to assume that preferably those capital goods would have been used by the remaining workers that produced the highest output per input of labor (see also Broadberry and De Pleijt 2021). Therefore, we would not directly expect a trend breach in the general rise in the use of medieval capital goods after the Black Death. This is what Figure 6 shows, as there seems to be no lasting influence on the use of capital goods by the Black Death (see also Claridge et al. 2024, arguing for the importance of the institutional change accompanying the Black Death for major changes in medieval wages).

5. Discussion

5.1. Correcting realism of illuminations

In this study detrending has been done with a combination of the prevalence of three different items that are pictured regularly in medieval handwritten books and that by themselves are not actual capital goods: trees, musical instruments and chairs. Each one of these symbolizes respectively the natural world, the cultural world and the domestic world. In their combination they should be relatively free of noise. A correction for 'realism' with only one of these items is of course also possible and produces results that are similar to those produced with the combination, and can be found in appendix C.

Figure 7. Prevalence of boats, detrended (black) and not detrended (red).
Source database



Correcting the series for the overall increase in realism over the period has a substantial impact on the results, lowering the overall increase in the prevalence of capital goods in the medieval economy. Taking our series for boats as an example, Figure 7 shows that detrending reduces the explained variance from 0.86 to 0.67. The slope coefficient is reduced by a factor 1.3. Not-detrending produces a higher outcome at the end and a lower one at its start.

A way of substantiating that detrending for increasing 'realism' is necessary is to look at the frequency with which midwives were depicted. In a previous section we presumed that the frequency of medieval midwifes and the

depiction of suicides would be stable over time. However, the not-detrended prevalence of midwives shows an increasing time-trend ($p < 0.01$) with a R-squared of 0.37, suggesting more deliveries with midwives over time in the Middle Ages. However, when corrected for 'realism' the slope is flatter and no longer meets conventional thresholds of statistical significance, and the R-squared decreases to 0.01. Likewise for suicides there is no time trend after applying our realism correction.

5.2. Time lags between inventions and their illustrations

There generally is a time-lag of a century between an invention and its depiction in an illuminated manuscript. Such a time difference has been observed in the database with eyeglasses, windmills and wheelbarrows. Therefore, for the few new medieval inventions the starting point of the regression has been taken to be two periods (one hundred years) before the first illustration of this device. The fact that our results are based for 95% on devices which were pre-medieval in their origin shows that this time-lag is not of much concern as it will not greatly impact the overall results.

6. Conclusions

In this paper we have used depiction of capital goods in medieval manuscript illumination to retrace the use of these goods in a pivotal period of long-run economic development.

Capital goods associated with all four economic sectors (farming, services, crafts, and construction) increased significantly during the 800–1600 period. This points to widespread growth in the use of capital goods. A wide range of capital goods, varying from ships to something as simple as the wheelbarrow, increased significantly in their prevalence over the Middle Ages. Other important capital goods that increased in prevalence in the full sample were the stern rudder, four-wheeled wagon, barrel, hammer, nails, cart drawn by horses, drill, ladder, treadwheel, urine flask, yoke, nails, cleaver, mechanical clock, heavy plough, spit, anvil, press, the rake and the spade. All but three of these were pre-medieval, suggesting that increased intensity and continuous improvements, rather than new inventions were key to understanding economic progress over this period.

During the medieval period not just the prevalence but the quality of most of these capital goods increased as well, which often made them more expensive. Combined, this process led to a gradually higher capital intensity during the Middle Ages. This study shows – contrary to the huge influence attributed to it in the literature – that the Black Death did not significantly increase capital intensity in medieval Europe. Rather, growth in the depictions of capital goods was highest in the High Middle Ages, and slowed after the Black Death

The geographical subsamples show more dynamism in northern Europe. Considerably more capital goods were in use there, and more medieval inventions were made in the north. We suggest that advances in the northern transport efficiency over land and sea further contributed to the increased economic dynamism in the north.

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Appendices

A.1. Database construction

During the corona lockdown and its aftermath a database was constructed containing descriptors of individual images in surviving manuscripts from the Roman period up to the Renaissance. The purpose of this database is to allow a peek at the contemporary uses of technology and various productive activities.

The basis for the database is the collection of over three thousand books and journals on manuscripts that have been described when making an estimate of the *Medieval manuscript production in the Latin West* (Buringh, 2011). Each illuminated page in a manuscript of which there is a picture in the library forms a separate entry in the current database. For every entry a number of essential descriptors are included: a manuscript's current whereabouts such as the country, place and library or private person where it is now located as well as its shelf marks (alfa-numeric and numeric) and the actual folio number of the page in question. Essential are also the work's author and its (abbreviated) title, just as the original country of production, and geographically more specific the place or area of origin and its actual date of copying, as well as its writer and/or artist (all if known, off course). Furthermore the nature of the writing material, its dimensions (height and width in mm) whether it was a codex or had another form and its size in numbers of folios, the language used and the script in which it was written were included too. Finally in the last column the source (author, book title and page or figure number) of the picture of the illuminated page in question was included, to enable a later glimpse of the actual figure. Currently the database contains 74.422 entries of illuminated pages that come from 10,901 manuscripts. Cross cultural comparisons are more complex and therefore this database has been limited to Christian and Jewish manuscripts.

Because of the low numbers of manuscripts picturing items in certain time windows, a distinction has been made between just two geographical and cultural regions: 'north' versus 'south'. The 'north' covers France together with all the other European countries located on a more northerly latitude than France. These others are: Austria, Belgium, Bohemia, Czech Republic, Denmark, Germany, Hungary, Iceland, Ireland, Latvia, Luxembourg, Netherlands, Norway, Poland, Slovakia, Sweden, Switzerland and the UK. The 'south' encompasses the Iberian Peninsula (Spain and Portugal), Italy, the Byzantine Empire (Türkiye), and countries with a predominantly Eastern Orthodox faith such as Armenia, Bulgaria, Croatia, Georgia, Greece, Montenegro, Russia, Serbia and Ukraine. There are a few Christian (mainly

Orthodox) and Jewish manuscripts from the Middle East and further afield that also have been attributed to the 'south'.

As the whole collection of books and journals consulted probably contains pictures of nearly one million pages of manuscripts there is plenty of room for enlargement of the current database. Care is taken to fill the database haphazardly in order to arrive at an unbiased sample concerning illuminated pages.

Using an 'illuminated page' as a criterion of inclusion into the database makes a clear definition of this concept necessary to avoid ambiguities. In some definitions all manuscript pages containing more than one color are considered to be illuminated (Brown, 1994, 69). For this database such a definition is on the one hand too narrow, as pages with monochrome pictures are then not included and on the other hand too broad, as any text page with only some pen flourishes in a different color would have to be included. In line with Backhouse (1997), in this study a page of a medieval manuscript becomes an entry in the database when it contains figurative representations on (one or more borders of) the folio. Inhabited (and with them historiated) initials (see: Brown, 1994, 72/68) on a folio are therefore considered to be part of such an illuminated page, just as carpet pages, canon tables and head pieces or illustrative elements at the end of chapters (see: Nordenfalk, 1970, 104). However, having one or more decorated initials (Brown, 1994, 47) on a folio does not automatically guarantee inclusion of a page into the database. Only when such non-inhabited initials were larger in size than a quarter of the height of the page was the page in question considered to have been 'illuminated' and included. The reason is that such a large initial required quite some work of the artist and created a visual effect that differed considerably from more plain text. The fact that this artist chose to concentrate on an initial and not use the available time to paint some figurative picture is relevant information. The criteria outlined above comply fully with the more than two hundred choices of illustrations made by Janet Backhouse in her book *The illuminated Page* in 1997. If none of a page's initials was inhabited or if a specific folio only contained plain text it was not included in the database. This also means that, in spite of their age and historical interest, palimpsests did not make it to the database. Concentrating on each page of a manuscript separately makes it easier to include the sometimes very different illuminators, places and time periods involved in completing one and the same manuscript. A well-known example is the *Tres Riches Heures du Duc de Berry*, which after its text had been copied was largely illuminated by the Limbourg brothers at the beginning of the fifteenth century but the codex was eventually finalized for a different patron by Jean

Colombe at the end of the same century. By concentrating on the various illustrations and what they represent and thereby not considering the actual text of a manuscript, any later textual additions are of no concern for the database.

One has to realize that the size of pages in manuscripts (and therewith their information content) could differ considerably. The smallest page in the current database has a mere 30 x 20 mm as its dimensions, while the largest measures 870 x 600 mm. Their respective surface areas differ more than eight hundred times. Also the total numbers of representations on a page could vary considerably. It starts at one (by definition) and mostly stays at one, but occasionally it could increase to up to 25 individual images as if it were a page in a medieval comic book. If possible and doable the images have been checked against their digital representations on the websites of the various libraries. This was especially helpful for getting to grips with details that were not always clearly visible in the actual image pictured in the various references. All the images on a page of a manuscript were considered. It also means that the database sometimes contains references to items not visible in the cited references because the medieval image had only partly been reproduced. The presumed intention of the medieval artist to represent an item was leading in classifying an item in the database. Whether or not we would currently find some depiction of an animal truly resembling a camel, elephant or a donkey was less relevant than the intention of the original artist. For an example of the process of scoring Figure 9 can be used. As previously indicated in the paper Figure 9 shows a windmill at the horizon and of course it shows trees and a chair. These three items were scored in the database, together with the essential descriptors of the manuscript in question.

Figure A1 shows an example of the items that can be found on an illumination in the Utrecht Psalter. In figure A2 we zoom in on the depiction of one particular item, stirrups, in the original Utrecht psalter and a later eleventh century copy, showing how contemporary capital goods were added even to copies of manuscripts.

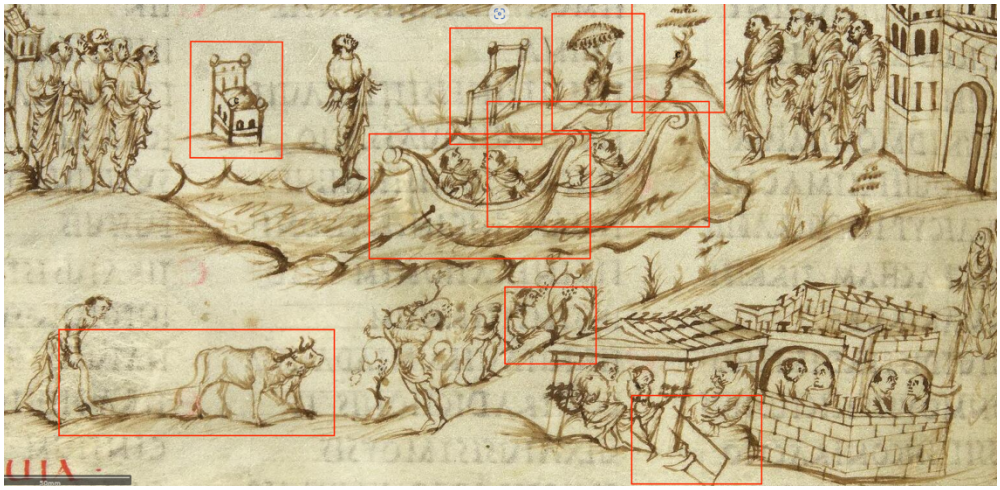


Figure A1. Capital goods and activities in red boxes in the Utrecht Psalter, f 62v. From left to right: ard, chair, boat, chair, boat, hoe, tree, tree, stocks.

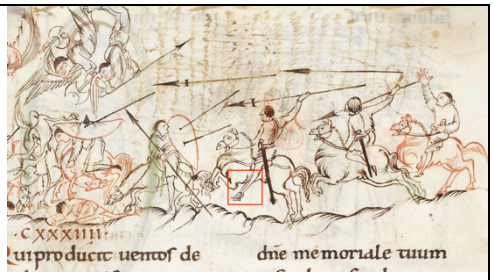
	
Horsemen in the Utrecht psalter, c. 830, f. 76v.	Horsemen in the Harley Psalter, c. 1030, f. 69r.

Figure A2. Capital goods depicted c. 830 and c. 1030, showing the addition of stirrups in a copy of an earlier manuscript.

The following alphabetical list of items and activities (often mainly visible in the staffage of an image, of course) has been scored per entry of the database. If one or more of those were represented in the medieval picture they were indicated with their name in the database at the entry in question and are then easily searchable and countable as such. One illuminated page could contain one or more of the following: accident, adze, alembic, anchor, anvil, aqueduct, ard, armillary sphere, astrolabe, axe, badge (pilgrim's), bath, barrel, beehive, bellows, bier, black people, boat, building, camel, cannon, capstan, cart, cart with oxen or horse traction, cauterizing iron, chair, charcoal, chessboard, chisel, churn, cleaver, clock, cogwheel, coins, compass, crowbar, crane, crane with treadwheel, crank, crossbow, crutches, demolition, dice, die, distaff, diver, diving bell, doctor, donkey, drill, eel, elephant, ergonomics, eyeglasses, fire, fishing rod, flail, flying machine,

flying scaffold, furnace, fyke, glasses, gridiron, hammer, handle, harrow, hayfork, healing, heavy (wheel) plough, hoe, hook, horse collar, horses, key, knife, ladder, lever, loom, market, mason, measuring rod, midwife, millstone, miracle, mirror, mortar, musical instrument, nails, net, organ, oven, oxen, pack animal, pestle, pickaxe, pincers, plane, plough (ard), plumbline, pottery kiln, press, pruning knife, pulley, rake, ramp, saw, scaffold, scales, scissors, screw, scythe, shipwreck, sickle, skates, skeleton, skull, sledge, sling, spade, spindle, spit, stern rudder, stirrup, stocks, suicide, submarine, swastika, sweep, tongs, transport, treadwheel, trebuchet, tree, trictrac, trident, trowel, tube, urine flask, wagon, wagon with oxen or horse traction, watermill, waterwheel, wheel, wheelbarrow, winch, windmill, winepress, winnowing basket, yoke, *zicht* (no English equivalent yet), zodiac.

Selected items and activities listed above are elaborated in more detail below. It must be stressed that the size of some of the items indicated in the database could at times be minimal in a medieval illumination. A ‘boat’ in the database could on the one extreme be a whole illuminated page carefully picturing a medieval sailing ship with its masts, rigging and crew or just a few quick lines suggesting a boat on water at the other end of the size spectrum. When an object was not visible on an image (for instance a stirrup completely covered by a piece of clothing of a horse rider) it has not been indicated in the database, even when one might plausibly assume that it was there. The current trend to digitize illuminated manuscripts has greatly helped with the interpretation of these sometimes confounding medieval pictures. If an item is not mentioned specifically in the following list elaborating the items the reader is referred to Wikipedia, where a similar description can be found as the one which has been used in this paper. Some items have been indicated with an umbrella concept as indicating all slightly different versions of an object would have not been workable. The products of a medieval cooper such as tubs, buckets or barrels, containing goods or liquids, have all been indicated just as a ‘barrel’.

Accident can either be a work related accident or more generally arising accidents such as a fall from a horse, a window, a wagon falling over, accidental arson, etc..

Astrolabe is also used for a quadrant.

Axe only as a tool, not as a weapon.

Barrel, bucket or a tub as the product of a cooper to transport or contain dry goods or liquids have all been classified under barrel.

Bellows whether or not with some mechanism attached to it.

Bier as a device for carrying loads, also known as barrow. A carrying pole used by two persons has also been classified as a bier, while a yoke (a carrying pole for one person) is classified separately.

Camel is both a Dromedary as well as a Bactrian camel.

Capstan or windlass.

Cart a two-wheeled vehicle for transport, pulled by either oxen, horses or other animals.

Chair is scored when in one of the pages of a manuscript there is a person sitting on a visible (part of) a chair and its cushions. It is used as one of the proxy's of realism. Also scored as a chair were a throne, bench, stool or a chest. When people were sitting on an animal, a rainbow, a rock, the ground, a branch, a tree or a bed this has not been scored as a chair. Also when people were sitting on an image, but when no part of a 'chair' was visible on the picture (because it was completely covered by clothes) this has not been scored as a chair.

Coins means that either actual coins can be seen represented on a page, or a purse/sack is handed over symbolizing a money transfer. Falsifiers (in Dante's Hell without actual coins) have not been classified under coins.

Ergonomics is classified in a situation when mortar is delivered at shoulder height, which makes it easier for the hodman to pick it up and carry it to the mason.

Fire is an open fire visible in house or outside on an illumination. Any medieval lamp in the dark has been classified as a fire because they all contained a fire. Risks of fire were great back then and often led to great disasters in the Middle Ages, as the building material used was often highly flammable.

Flying machine any contraption meant to transport its occupants through the air.

Flying scaffold a work space of construction workers high up in the air mounted on horizontal poles sticking out of a wall, with no direct contact with the ground such as an actual scaffold. Due its construction without any guardrails it had a high risk of falling accidents occurring.

Gridiron or grate has been classified as a gridiron.

Healing in the database is a depiction of a doctor or a patient, irrespective of the final outcome of the medical intervention in question. Representations of

medical instruments were included under healing. (The numerous pictures of medieval herbals and of healings not by doctors but by biblical figures or saints, classified as “miracles” in the database, have not been included under the classification healing. Also excluded were circumcisions, medicinal baths and pictures of skeletons, which have in some publications been considered medical illustrations, see amongst others: MacKinney (1965) figs 85a, 94a,b and Murray Jones (1998) figs 13, 14, 24.)

Heavy (wheel) plough a heavy moldboard plough with coulter either with or without a wheel. The heavy plough turns over a furrow, which at the same time ploughs the in medieval times ubiquitous weeds under the soil. The capital investment for a heavy plough and its draught animals is considerably larger than for an ard.

Horses means traction by one or more horses

Loom either a horizontal or vertical loom for weaving cloth or a carpet.

Market means either selling stuff in a shop or stall or making a commercial deal in the open air. A travelling merchant with goods doing his business or an image of a merchant or a farmer transporting products to sell has been classified as a market too. Also images of medieval craftsmen in combination with their customers were considered to be markets. While images of craftsman solely making products or an image of people drinking in inns were not considered markets, though as a rule the persons running these business were financially compensated for their products or services.

Mason also can mean a carpenter or anyone active at doing building activities.

Midwife any scene of a woman giving birth assisted by one or more other women.

Miracle is any miraculous healing from a biblical story or a saint’s life or a representation of the bird *Caladrius* (used by healers to find out if a patient would live or die).

Musical instruments existed during the whole of the study period and are used as one of the proxy’s for realism in medieval manuscripts. When an image represented one or more (hunting) horns, drums, bagpipes, flutes, harps, lyres, organs or any other musical instrument this was scored in the database as a ‘mus instr’ for that entry. It thereby did not matter whether or not these instruments were played by humans or by animals (drolleries) in the image or if the objects in the image were only suggesting a musical instrument such as playing music with tongs or the lower jaw of a donkey.

Oxen means traction by one or more oxen/cattle

Pack animal is any animal carrying a load.

Pincers of carpenters and tongs of blacksmiths have all been classified as pincers.

Plough is an ard or scratch plough the older type of plough is mainly used for lighter soils. It does not turn over a furrow.

Screw is a pole with a visible screw thread.

Shipwreck any ship in a storm or in such utter distress that it may lead to loss of life (if it were not for some often occurring divine intervention in an illumination).

Stirrup either one or more stirrups or one or more of their straps have been classified as a stirrup.

Stocks or pillory are all classified under stocks.

Submarine any contraption to house or transport humans or animals under water.

Sweep a well sweep or shaduf

Transport stands for personal lifting or transporting some load on foot.

Tree is used here as one of the proxy's for realism in medieval pictures. Sometimes trees even play a role in the Bible or were mentioned explicitly, such as during the Creation and in the story of Adam and Eve in paradise or in a dream of Nebukadnezar, to name only a few instances in the Old Testament. Therefore representations of trees in manuscripts abound. However, Otto Mazal (1988) is the single author to give a full podium to trees in historical manuscripts in his book *Der Baum*. In line with his choices of pictures of trees we have defined an entry in the database to contain a tree if on the image in question an individual tree was visible. This does not necessarily have to be a whole tree containing all the four different elements that together form a tree: its roots, trunk, branches and crown. Just one or more of these being individually visible would suffice to count the entry as having a tree. In line with Mazal (1988, 89) a grapevine has been considered a tree in this study. A regularly represented biblical tree is the 'tree of Jesse', which also can be considered to be a sort of holy family tree. Family trees, tables of consanguinity, 'trees of vices' and 'trees of virtues' in manuscripts have only been counted as trees when they were pictured with branches and/or a trunk. Whenever such allegorical trees were represented by mere

lines without any indication of its treelike nature they were not counted as trees.

Urine flask a glass vessel (*matula*) was used for uroscopy by doctors or by animals in drolleries. As such the urine flask was the medieval symbol for a doctor.

Wagon a (three- or) four-wheeled contraption to transport people or loads with or without spokes. Whether or not a wagon also had a moveable fore carriage mostly cannot be estimated reliably from a medieval image.

Watermill is a mill with either a vertical or a horizontal waterwheel as a driving mechanism.

Windmill is either a horizontal or a vertical windmill. The vertical windmill was a medieval invention that helped in the economic take off in the Latin West (see Van Bavel et al, 2018).

Zicht is a short scythe-like instrument used in the late Middle Ages to cut grain in combination with a grain hook, it was used instead of a sickle.

A.2. Database validations

While we prefer to analyse the database at a higher level of aggregation, certain individual items can be used to check the reliability of our approach. As a first check on the trends of medieval capital goods implied by our methods we also counted the frequency with which two –plausibly unchanging – practices were depicted in manuscripts: midwives and suicides. Because the practice of childbirth remained unchanged over the medieval period, relying solely on midwives for expert assistance, we would expect their depiction to remain similarly consistent over time. For suicides a comparable reasoning can be set up. Because the biblical and classical texts featuring suicide remained constant, and because the Church did not tolerate suicide throughout the period, we would expect no trend in their artistic depictions. Indeed, our data show no statistically significant trends for midwives and suicides (midwife: slope = 0.004, p-value > 0.1; suicide: slope = 0.001, $p > 0.1$).

We can also validate our data using common agricultural tools where we expect similar trends between the North and South. Depictions of the ard trend downward slightly slower in the North, but this difference is not statistically significant (difference = 0.02, $p > 0.1$). Likewise, the hoe show no difference in trend (delta ≈ 0, $p > 0.1$). By contrast, the heavy plough—

typically associated with the clay soils of North-Western Europe (Andersen 2016; White 1962, though these soils did also exist in the South, the Po Valley in particular), shows a distinct regional pattern: our data reveal only a single southern depiction, compared to growing northern usage from 1000 onwards.

B1. Regression estimates of time trends.

Table B1. Regression estimates of slopes of time trends for share of manuscripts with a given item. (source database)

item	Estimate	Std. Error	t value	p-value	R^2	N
anchor	0.006	0.007	0.764	0.470	0.097	9
anvil	0.010	0.002	4.492	0.001	0.520	16
ard	-0.023	0.008	-2.906	0.027	0.737	8
axe	0.014	0.006	2.201	0.045	0.212	16
barrel	0.035	0.005	6.739	0.000	0.744	14
beehive	-0.008	0.003	-2.572	0.024	0.327	14
bellows	0.011	0.006	1.669	0.129	0.283	11
bier	0.005	0.004	1.123	0.280	0.084	16
boat	0.053	0.012	4.294	0.001	0.669	16
capstan	-0.002	0.003	-0.590	0.566	0.038	14
cart	-0.022	0.007	-3.176	0.007	0.538	16
cauterization	0.005	0.004	1.519	0.167	0.250	10
chisel	0.010	0.009	1.195	0.253	0.186	15
cleaver	0.003	0.001	5.118	0.000	0.657	14
clock	0.013	0.002	7.917	0.000	0.892	8
cogwheel	0.005	0.002	2.028	0.062	0.392	16
compass	0.002	0.005	0.513	0.617	0.031	14
crane	0.006	0.005	1.162	0.275	0.125	11
crank	0.006	0.006	1.020	0.332	0.141	12
demolition	-0.007	0.003	-2.029	0.073	0.419	11
distaff	0.009	0.004	2.123	0.055	0.284	14
drill	0.006	0.001	10.140	0.000	0.879	14
fishing.rod	0.000	0.004	-0.028	0.978	0.000	13
flail	0.009	0.004	2.231	0.053	0.434	11
flying.scaffold	0.004	0.004	0.930	0.376	0.068	11
furnace	0.001	0.008	0.121	0.905	0.002	14
gridiron	-0.003	0.002	-1.107	0.292	0.095	13
hammer	0.035	0.012	3.036	0.010	0.571	15
harrow	0.006	0.003	2.147	0.051	0.435	15
hayfork	0.008	0.004	1.811	0.097	0.296	13
healing	0.010	0.008	1.325	0.206	0.103	16
heavy.plough	0.010	0.003	3.527	0.003	0.564	16
hoe	0.005	0.007	0.689	0.503	0.049	15
hook	0.005	0.002	2.456	0.030	0.344	14
horse.collar	0.015	0.007	2.134	0.062	0.498	11

item	Estimate	Std. Error	t value	p-value	R^2	N
key	0.001	0.007	0.133	0.896	0.002	16
ladder	0.032	0.007	4.699	0.000	0.634	16
loom	0.003	0.003	0.968	0.361	0.102	10
mason	0.005	0.007	0.657	0.523	0.032	15
measuring	-0.016	0.006	-2.526	0.025	0.454	15
millstone	-0.006	0.004	-1.633	0.128	0.280	14
mortar	0.004	0.003	1.274	0.234	0.040	11
nails	0.014	0.003	4.889	0.000	0.489	14
net	0.005	0.005	0.969	0.352	0.098	14
oven	0.004	0.002	2.095	0.058	0.217	14
pack.animal	0.003	0.002	1.431	0.183	0.133	12
pestle	0.001	0.002	0.397	0.698	0.009	15
pickaxe	0.014	0.005	2.839	0.015	0.502	14
pincers	0.013	0.006	2.346	0.037	0.292	14
plumbline	0.005	0.003	1.741	0.105	0.289	15
press	0.004	0.001	3.382	0.005	0.597	14
pruning.knife	-0.003	0.007	-0.426	0.677	0.020	14
pulley	0.010	0.008	1.171	0.266	0.174	13
rake	0.007	0.002	3.322	0.005	0.537	16
ramp	0.006	0.003	2.090	0.063	0.231	12
saw	0.000	0.004	-0.074	0.942	0.001	12
scaffold	0.006	0.004	1.349	0.204	0.162	13
screw	0.003	0.002	1.568	0.141	0.117	15
scythe	0.007	0.006	1.166	0.266	0.136	14
sickle	-0.009	0.004	-2.031	0.063	0.184	15
sledge	0.005	0.004	1.406	0.197	0.328	10
spade	0.020	0.005	3.847	0.002	0.509	16
spindle	0.006	0.004	1.341	0.207	0.166	13
spit	0.005	0.002	3.346	0.005	0.418	15
stern.rudder	0.035	0.007	5.282	0.001	0.731	10
transport	0.032	0.012	2.597	0.021	0.419	16
treadwheel	0.006	0.001	5.950	0.000	0.713	15
trident	-0.006	0.002	-3.696	0.004	0.404	13
trowel	0.007	0.005	1.427	0.181	0.121	13
urine.flask	0.013	0.003	3.932	0.002	0.450	15
wagon	0.027	0.008	3.501	0.004	0.596	16
watermill	0.014	0.007	2.049	0.061	0.429	15
wheelbarrow	0.012	0.002	6.609	0.000	0.875	11
winnowing.basket	0.006	0.003	2.037	0.072	0.394	11

item	Estimate	Std. Error	t value	p-value	R^2	N
yoke	0.002	0.000	4.601	0.001	0.552	12

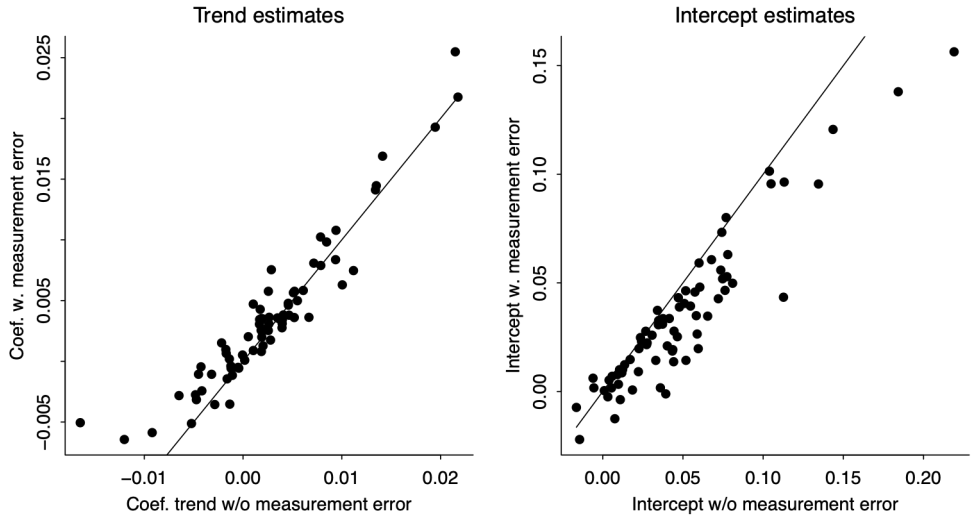
B.2. Measurement error models of time trends

A potential issue with the OLS estimates of the time trends of the prevalence of illuminations with capital goods in manuscripts is that we face greater uncertainty in earlier periods, partly driven by the smaller number of surviving manuscripts. To address this, we also estimate the slopes using a Bayesian model that accounts for this varying uncertainty:

$$p_t^{obs} \sim N(p_t^*, SE_{p,t})$$
$$p_t^* \sim N(\beta_0 + \beta_1 t, \sigma)$$

This model is estimated separated for each capital good *c*, which we omit for clarity. Here, p_t^* represents the true share of manuscripts containing an illumination of a specific capital good century t; $p_t^{obs}$is the observed share, and $SE_{p,t}$ is the standard error associated with this observation. In this Bayesian framework (McElreath 2016, Stan Development Team 2025), p_t^* is a latent parameter to be estimated. The resulting slope coefficients and intercepts are plotted against the estimates not incorporating measurement error in Figure B1. The differences between the two sets of estimates are minor and show that if anything, incorporating measurement error lowers the intercepts and increases the slopes of the time trends in capital goods.

Figure B.1. Comparison of slopes of OLS and measurement error models.



B.3. Poisson models

An alternative way to estimate trends is with a Poisson regression, where the number of illuminations containing a given capital good, n_{ct}, is regressed on time, *t*, while controlling for the total number of manuscripts m_t and realism using our realism index p_{tr}.

$$E[n_{ct}] = \exp(\beta_0 + \beta_1 t + \beta_2 \log(m_t) + \beta_3 p_{tr})$$

We compare the results obtained from this model for all combined capital goods with the OLS results in table C1 below.

Table C1. OLS and Poisson models of the share and number of manuscripts containing capital goods. Heteroskedasticity-robust standard errors between parentheses.

Dependent Var.:	Share MS w. capital goods	MS w. capital goods	MS w. capital goods
Constant	0.0627 (0.2970)	-3.980*** (0.4209)	-1.314*** (0.2958)

century	0.0912** (0.0252)	0.2189*** (0.0313)	0.0778** (0.0242)
log(nms_unheaped)		0.9709*** (0.0688)	0.8849*** (0.0421)
log(index_realism_indexed)			1.187*** (0.1540)
Family	OLS	Poisson	Poisson
Observations	16	16	16
Squared Cor.	0.56973	0.97976	0.99487
Pseudo R2		0.94993	0.96573
BIC		189.30	134.96

C.1. Realism corrections

Figure C1. Three series of everyday objects and a combined index to correct for realism in medieval manuscript illuminations, 800–1550.

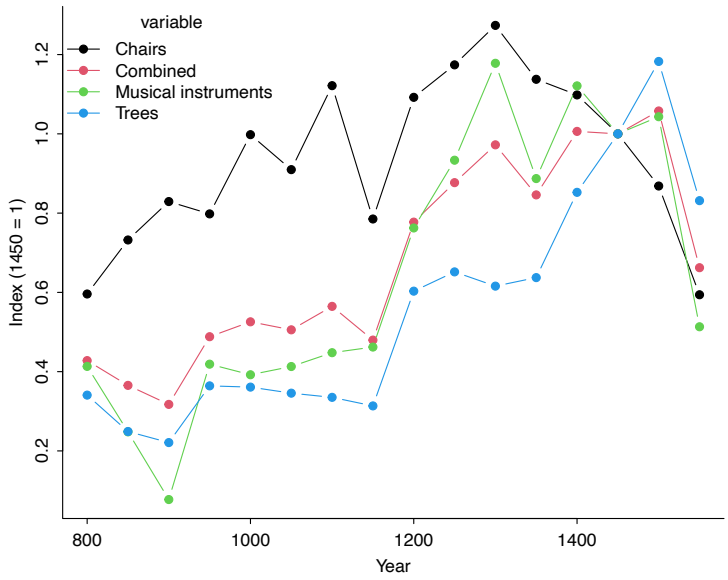
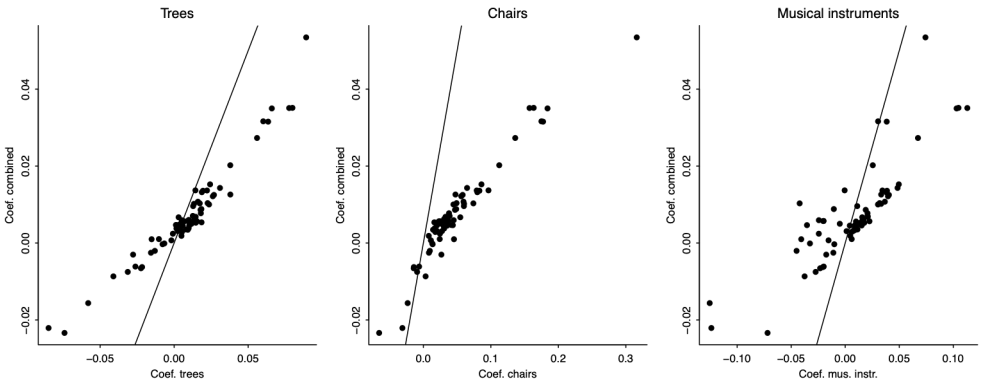


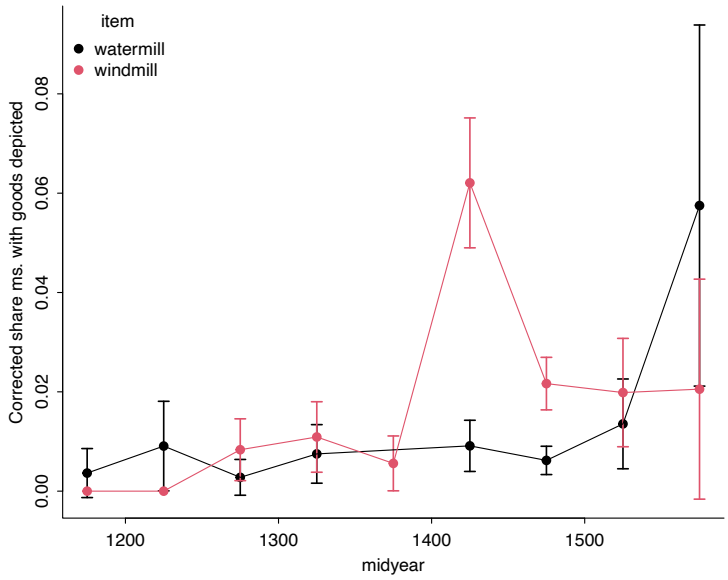
Figure C.2 Slope coefficients for all capital goods in the database with realism corrections based on one indicator only (x-axis) compared with combined index (y-axis).



C.2. Culture and capital good depictions

A more subtle issue is how objects were depicted in the first place. This can be seen in Figure C.3, which shows the detrended prevalence in the database of windmills and watermills between 1150 and 1600. This is the one item originally included in the database that we later assessed had to be omitted because of the special role the windmill played in medieval painting.

Figure C.3. Detrended prevalence of windmills and watermills. Source: database



Watermills were a pre-medieval technology. Windmills were invented in the twelfth century, but only started to get pictured around 1260. Therefore before 1250 watermills are pictured more frequently, after that windmills get the upper hand. At first glance such a general difference in prevalence in manuscripts seems to suggest that windmills were more prevalent than watermills in the Middle Ages. However, the reason for a higher prevalence of windmills in manuscripts is purely visual. Because water flows downwards, watermills are always lying in a valley along some stream or mill race. Their buildings are not conspicuous in a landscape and are easily overlooked. The wheel itself is mostly visible from only one of the four possible directions from which it can be seen. Often the actual building shields the wheel from view. And without a visible waterwheel a building bordering a stream cannot be classified as a watermill. This explains their relative underrepresentation in the database. Windmills, on the contrary, were

constructed at higher places to catch the wind to power the mill. They are therefore clearly visible at the horizon.

The second peculiar feature of Figure C.3 is that in the first half of the fifteenth century an over fourfold higher prevalence of windmills is observed than in previous or later half-century periods. Next to the visibility aspect one could look for specific economical or technological reasons that can explain such a sudden burst of windmills. Economic or technical reasons are not plausible, however, as this spike is not substantiated by any of the studies done on distributions of mills (Langdon, 2004, 36 even observes a downward trend in England after 1350). The explanation for this surprising spike is again cultural. Art historians generally say that landscape painting started in the first half of the fifteenth century. Clark (1976, 23) indicates that the first modern landscapes were exceedingly small – only about three inches by two inches. They were painted between 1414 and 1417 in a manuscript known as the *Hours of Turin*, for the Count of Holland (Figure C.4).

Figure C.4. Saint John the Baptist and Christ in a landscape (Turin, Mus Civ, ms 47, f 93v, detail).

In Figure C.4 the famous medieval artist Jan van Eyck pictured a mountainous landscape in the Holy Land with a receding horizon. It is one of the very first realistic landscape paintings. In the foreground saint John is baptizing Christ in the river Jordan. At the right people are watching his

baptism. A castle projects its mirror image onto the water of the river. In the background the landscape gradually disappears in a vague blue hue, however, it also shows a windmill at the horizon. By the beginning of the fifteenth century landscape painting had spread over Europe. Windmills were preferably constructed at higher places and are clearly visible in the landscape. Because of this sudden emphasis on the horizon in the fifteenth century artists pictured windmills even more than before.

Generally, watermills were to a greater extent involved in the process of milling grain and industrial applications. Figure C.3 shows that watermills did not see a similar sudden surge in their prevalence in manuscripts in the fifteenth century. Contrary to windmills their numbers in England had roughly remained constant during the fourteenth and fifteenth centuries (Langdon, 2004, 37). This is an additional argument that this sudden windmill-spike was not caused by developments in the demand of milling. It shows that it has everything to do with the greater visibility of windmills and the extra attention they received by medieval artists who were exploring the horizon as a new area of interest. In short, cultural changes may distort the general picture. However, as far as we are aware, it has only been the case for windmills in this study. Therefore, we eventually omitted windmills from the list of capital goods of this study. Previous calculations show that including windmills would, however, makes no substantial difference to the overall results of this study.

D. Key sectoral developments
D.1 Service sector

Figure 4 presents a significant upward trend in the overall use of capital goods in the service sector. It also shows that in the full sample seven of the 20 capital goods used in the service sector (Table 2) turned out to be prevalent significantly more ($p < 0.01$). These were: boats, the stern rudder, the four-wheeled wagon, wheelbarrow, barrel, urine flask and yoke. One capital good was found significantly less: the two-wheeled cart. The prevalence of thirteen others didn't change significantly.

The number of manuscripts depicting boats or ships increased significantly. This plain increase in numbers, however, does not yet take into account that on average the size of medieval vessels gradually increased too. The types of the ships, which at the beginning generally were simple one-masted vessels with either a square or a lateen sail, at the end often had developed into full-rigged ships with three masts. This indicates an increasing capital intensity beyond what our method can capture, as these later boats were considerably larger, more seaworthy and more expensive too.

The prevalence of a stern rudder, a steering device, also increased significantly. This rudder – attached with a pre-medieval pintle and gudgeon system to the stern of a boat – was probably developed in the eleventh century in Nordic waters. It is one of the few medieval inventions, and replaced the single quarter rudder that was used previously on Nordic ships. As these became bigger a single quarter rudder was no longer sufficient. Shipping in the Mediterranean did not suffer from similar steering problems because always two larger quarter rudders had been used there. These were attached to the hull quite differently and were more sturdy. Mediterranean quarter rudders were therefore less accident prone than the single Nordic quarter rudder. Eventually ships with stern rudders turned out to be superior in their sailing qualities in rough seas and were adopted in the Mediterranean too at the end of the Middle Ages. A stern rudder (the pintle and gudgeon system itself) required the use of then expensive metal, while for a quarter rudder no metal to speak off was needed.

In the service sector the four-wheeled wagon was used increasingly. This was to the detriment of the two-wheeled cart in general, which at first had been the main means of transport but eventually was used significantly less. The two-wheeled cart drawn by the slower oxen was used less, while one drawn by the quicker horses was used more, in agreement with the findings of Langdon (1986). A four-wheeled wagon is approximately twice as expensive as a two-wheeled cart, but has a number of advantages. The first

one is that only a single person was needed as a driver, while for the same load carts needed two persons as drivers. The second advantage is that the axle pressure of a four-wheeled wagon generally is lower, which means it can move easier over uneven terrain.

The next device that was used significantly more was the wheelbarrow, also a medieval invention. It was probably developed in northern Europe around the twelfth century from a handbarrow, a two-person lifting device used to transport goods. A wheelbarrow is essentially a wheel added to a handbarrow, with the advantage that one man now could transport the same load as two with a handbarrow. Of course adding a wheel makes this implement more expensive than a handbarrow.

In the service sector the barrel was used significantly more too. A medieval wooden barrel was in fact used similarly as our modern container. Barrels were strong and protected their contents from rough handling and from the elements during transport. Barrels came in a number of more or less standardized volumes to transport liquids. But also were used to ship dry goods such as flour, powder and even manuscripts. Because of its bilge a barrel could be easily rolled or turned by one man, who could so manage a considerably larger weight than he could possibly ever have carried.

Urine flasks increased significantly in their prevalence, indicating more doctors or quacks. The preeminent symbol of a medieval doctor was the urine flask. In the past, peeking at the pee of a patient was a physician's most important way of coming up with a diagnosis. A diagnosis could then also be derived by feeling a patient's pulse or consulting the stars. Despite these other means uroscopy took precedence in medieval medicine. This practice, used for any ailment, was convenient for both doctors and patients, as only the urine had to travel.

Transporting loads is easier for a human when using a yoke. Its use increased considerably. As yokes were mainly made of wood their cost was low.

D.2. Farming

In the agricultural sector the use of capital goods increased. In the full sample five of the 19 devices (Table 2) increased ($p < 0.01$) in prevalence and one decreased. The use of the heavy plough, the spade, the rake, trident and press increased, while that of the ard (scratch plough) decreased.

The main capital investment of a medieval farmer in movable capital goods would have been in his plough and its traction team. The ard or scratch

plough was universally used at the beginning of the study period, though the heavy plough was known in some parts of Europe. An ard does not turn over the soil but only scratches it and ploughing twice – in a perpendicular pattern – was necessary. The heavy plough turns over the soil (and the weeds). Later less weeding is necessary and ploughing only once suffices. Because it cost more power to pull, the traction team of a heavy plough had to be larger. At first oxen pulled the ploughs. Later they were succeeded by horses, which were both stronger and faster. In northern Europe the ard was generally substituted by the heavy plough in due time. A heavy plough, with more metal, is a larger capital investment than an ard, and horses were more expensive to keep than oxen, because they needed more nutritious fodder and were not consumed afterwards. However, all in all, the heavy plough pulled by horses generally had economic advantages above a scratch plough with oxen. The increasing cerelization as a result of the rising prevalence of heavy ploughs during the Middle Ages led to a greater demand of milling.

The use of the spade increased too over the medieval period. Though the form of the medieval spade looked similar to ours it was in fact quite different. The spade was completely made of wood including its thick blade, with only a thin iron sheath covering the wood at its ‘cutting’ edge. This thick wooden blade made it strenuous to operate a medieval spade. Only at the end of the Middle Ages the full metal blade started to be used. This made spades much sturdier and also easier to operate, as they now also had become sharper. But because metal was expensive this conversion increased its capital intensity. Spades were used some five times more in northern Europe than in the south. That this result is not an artefact of the method applied in this study can be shown by the use of the hoe, which was virtually similar in ‘north’ and ‘south’.

Also the use of the rake increased. This simple implement (made of wood of course) was quite similar to the hay rakes still used nowadays. Even more than the spade it is an implement that is nearly only found in the ‘north’. This is because rakes were often used in combination with scythes. And in the ‘south’ scythes were rare, as people there mainly used sickles for cutting grain or grass.

The press was used more too. This was an ancient capital good that needed quite some investment. The other farming implement that increased in usage: the trident, did not change significantly in during the study period.

D.3. Construction

In the construction sector the prevalence of six capital goods increased significantly in the full sample: the hammer, ladder, drill, nails, treadwheel and the wheelbarrow. The pre-medieval treadwheel is often found in combination with a crane. Generally, a treadwheel is a huge – more than man-sized – wooden wheel in which people walked upright to let it rotate. Using a rope and pulleys the rotating axle in combination with the force by the weight of the walkers was used to lift heavy loads with a crane. The prevalence of cranes did not change significantly in the full sample. However, in the subsample of the 'north' cranes increased significantly while they decreased significantly in the south.

Nails were pictured significantly more over the study period. Nails were always handmade by smithies and because of the increasing use of iron their price gradually decreased making them more common.

D.4. Crafts

In the crafts sector the use of seven capital goods increased significantly in the Middle Ages: the hammer, drill, anvil, spit, barrel, cleaver and the mechanical clock.

Hammers were universally used pre-medieval capital goods, which were available in numerous different sizes and forms. Various specialized uses were made of them in the many different crafts varying from goldsmiths to blacksmiths, cobblers as well as numerous others.

A similar story can be told for drills. Drills were used by carpenters, cabinet makers, wheelwrights, joiners, ship builders and other crafts working with wood. What cannot be seen in the various illuminated pages is the quality of the metal a drill is made of, which gradually increased as better qualities of steel were produced.

Mechanical clocks driven by weights were a thirteenth-century invention, that spread over Europe fast. It is a marker for the fine mechanical skills developed by the time. But in a more sturdy and heavy form large cogwheels were used in mills to change the direction of motion induced by the vertical waterwheel (or sails) into a horizontal motion driving the millstones. They were also used as a gearing mechanism to adjust the speed with which these devices were turning. Cogwheels of various sizes are a complex form of mechanical engineering that expanded considerably during the Middle Ages.

The barrel as the final product of the medieval cooper has been discussed previously. It was also widely used by other crafts such as glassblowers to

package their products safely for transport. Remarkable is to note, that over time the use of barrels only increased significantly in the ‘north’ and not in the ‘south’.

The cleaver, used by butchers, is the final capital good in this sector that increased significantly.

Interestingly, the geographical subsamples ‘north’ and ‘south’ are quite different when individual capital goods attributed to the crafts sector are considered. The ‘south’ only had one capital good whose prevalence increased significantly: the bellows. While the ‘north’ had nine: drill and barrel –already seen above for the full sample – and also the anvil, saw, oven, spit, distaff, and spindle.

The bellows is pre-medieval tool. It was used in all crafts that regularly used a fire such as brewers, bakers, distillers or dyers to kindle a fire or to achieve higher temperatures, for instance by a blacksmith who needed red hot metal. When melting metal from ore only the size of the bellows differed from that of the household appliance. Such bellows were then often mechanically driven by a waterwheel, making it a more capital intensive contraption.

Saws, which increased significantly in the ‘north’ were generally used by all crafts working with wood. The quality of a saw is heavily dependent on the quality of the metal it is made off. This cannot be seen in the various illuminated pages but it gradually increased as better qualities of steel were produced. The raking of a saw changed from a pull stroke to a more efficient push stroke (visible in the database). Also the form of the saw was adjusted so a saw could now be used by only a single person instead of the two persons which were customary in the beginning.

The other device often used by blacksmiths and others: the anvil had a significantly increasing prevalence in the ‘north’, just as that of the oven, spit, distaff and spindle, which each in their turn were used by various crafts and trades.

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